TITLE: The New Approach to the Single-Electron Electrometer Design

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The new approach to the single-electron electrometer design

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Abstract. We report on new two types of single-electron tunneling (SET) transistor-electrometer. The both transistor types comprised two chains of tunnel junctions instead of two single junctions. In the first case (Type I) the role of junctions plays the shadow-evaporated chains of stack tunnel Al/AlO$_x$/Al junctions with an island in between. In the second case (Type II) there were two highly resistive Cr thin-film strips ($\sim$1 μm long) connecting a 1 μm-long Al island to two Al outer electrodes. Our transistor demonstrated very sharp Coulomb blockade and reproducible, deep and strictly e-periodic gate-modulation in wide ranges of bias currents I and gate voltages V_g. In the Coulomb blockade region ($|V| \leq$ about 0.5 mV) we observed strong suppression of cotunneling current enabling to measure appreciable modulation curves $V(V_g)$ at current I as low as 100 fA (Type II transistor). The noise figure of our SET transistors was found to be similar to that of typical Al/AlO$_x$/Al SET transistors, viz. $\delta Q_x \approx 3.5 \div 5 \times 10^{-4} e/\sqrt{\text{Hz}}$ at 10 Hz.

Introduction

The SET transistor is a system of two ultra-small metal-insulator-metal tunnel junctions attached to a small island which is capacitively coupled to a gate electrode. Due to their considerable resistance, $R \gg R_Q \equiv \hbar/4e^2 \cong 6.5$ kΩ, the tunnel junctions ensure quantization of charge on the island. On the other hand, the junctions still make possible the correlated charging and discharging of the island by individual electrons when temperature is sufficiently low, $k_B T \ll E_c$. Here $E_c = e^2/2C_\Sigma$ is the charging energy, $C_\Sigma = C_1 + C_2 + C_0 + C_g$ is the total capacitance of the island which includes the capacitances of the junctions $C_{1,2}$, self capacitance of the island C_0 and capacitance between the island and gate electrode C_g. Transport of electrons is controlled by the transistor gate polarizing the island and therefore changing the Coulomb blockade threshold. Increase of the gate voltage V_g causes a stepping increment of the number of electrons on the island and this leads to e-periodic dependence of the $I - V$ characteristic on V_g. Due to this effect the transistor provides a means for measuring the polarization charge on its island with sub-electron accuracy. This property of SET transistors was successfully exploited in many experiments on measuring and monitoring sub-electron quantities of charge in mesoscopic systems (see some examples in Refs. [1], [2, 3, 4] and [5]). Different materials and methods have been used for fabrication of SET transistors. Although substantial progress in fabrication techniques has been done, there is still a demand for devices simple in fabrication, less subject to the electrical shock destruction and with good electric parameters. In this paper we present a new type of SET transistor-electrometer having potential to meet these requirements. The idea of our work was to fabricate and characterize a metallic transistor with chains of stack tunnel Al/AlO$_x$/Al junctions (Type I) or with high-ohmic ($R \gg R_Q$) Cr-film microstrips (Type II) replacing the traditional (oxide) tunnel barriers between the

island and outer electrodes. The junctions of this type should, to our mind, also ensure sufficient isolation of the island leading to the correlated electron motion across the device [6]. Below we report the SET characteristics of our device.

1. Sample fabrication

The structures of both types were fabricated by the shadow evaporation through a suspended mask [7] on Si substrate buffered by AlO_x layer (about 200 nm thick). The structures of Type I were fabricated by sequential evaporation of the chain islands through the same opening in the mask. After each evaporation the angle of the evaporation was slightly changed to shift the the islands a little from each other. The oxidation were done between each evaporation. By this way we got a very compact chain (about 100 nm long) of stack tunnel junctions.

For the structures of Type II the fabrication process was carried out *in situ* by three steps to obtain reliable metallic contacts between Cr and Al films. First, the Al film 10 nm thick was deposited by e-gun at the first angle. It formed the bottom layers of the island and outer electrodes. Secondly, the Cr film of thickness $6 \div 8$ nm was evaporated at small residual pressure ($\approx 10^{-5}$ mbar) of oxygen. This evaporation was made at another angle to overlap the bottom Al layer giving rise to the electric connection of the island and outer electrodes. The nominal contact area between Al and Cr layers was 100 nm by 120 nm. Finally, the second Al layer (about 30 nm thick) was evaporated at the first angle so that the ends of Cr strips were clasped by Al electrodes from bottom and from top. The gate electrode was positioned near the island. The top view of the resulting structure is presented sketchy in Fig. 1 where the stray metal shadows are not shown for the sake of clarity.

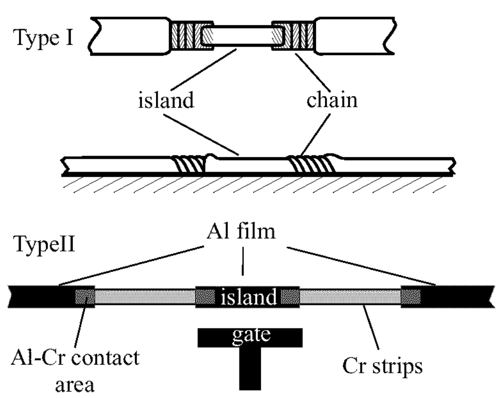

Fig. 1. The geometry of the Cr-film transistor structure. The width of the strips (about 100 nm) is shown somewhat larger for clarity.

2. Results and discussion

The transistor of the first type comprised two chains of tunnel junctions instead of two single junctions. We have studied the electrical and noise properties of the device. The transistor has shown periodical modulation curves with slowly variable amplitude depended on background charges on the islands located between junctions in the chains. The measured value of charge noise was to be closed to a typical value for a planar transistor structures: $\delta Q_x \approx 3.5 \times 10^{-4} e/\sqrt{\text{Hz}}$ at 10 Hz and mostly determined by the size of its central

island (~0.5 μm). In comparison with traditional SET transistor (two single junction structure) our devise had considerably lower cotunneling current that can be important for the transistor being used in electronic circuits as a current switch. The transistor of the second type had even more unusual design: it comprised two highly resistive Cr thin-film strips (~1.2 μm long)) connecting a 1 μm long Al island to two Al outer electrodes. These resistors replace small-area oxide tunnel junctions of traditional SET transistors. Our transistor with a total asymptotic resistance of 110 kΩ showed a very sharp Coulomb blockade and reproducible, deep and strictly e-periodic gate modulation in wide ranges of bias currents I and gate voltages V_g. In the Coulomb blockade region, we observed a strong suppression of the cotunneling current allowing us to measure appreciable modulation curves $V(V_g)$ at currents I as low as 100 fA. The noise figure of our SET was found to be similar to that of typical Al/AlO$_x$/Al SET transistors, viz. $\delta Q_x \approx 5 \times 10^{-4} e/\sqrt{\mathrm{Hz}}$ at 10 Hz.

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